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TUTORIAL

Modeling and Dynamic Performance of Renewable Energy Systems

P. Pourbeik and N. Miller

SC C4 – System Technical Performance

INTERNATIONAL COUNCIL
ON LARGE ELECTRIC SYSTEMS

Modeling and Dynamic Performance of Renewable Energy Systems

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Content

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Tutorial Content

- Overview of Renewable Energy Systems (5 minutes)
- Dynamic Performance of Renewable Energy Systems (35 minutes)
- Modeling of Renewable Energy Systems (35 minutes)
- Questions and Answers (15 minutes)

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Overview of Renewable Energy Systems

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Overview of Renewable Energy Systems

What are renewable energy (RE) systems?

- Wind Energy
- Solar Energy (photovoltaic and solar thermal)
- Hydro Power Plants (modern variable speed)
- Wave and Tidal Energy
- Etc.

Our Focus here will be on Wind and Photovoltaic Systems

Note: Solar Thermal is typically a synchronous generator interface

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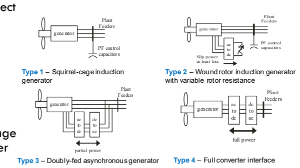
How does RE interface with the Grid?

- Earlier technologies of wind generators were direct connect induction generators
- These do still exist and are important to model
- However, the majority of RE today use power electronic interfaces
- Even advance pumped storage hydro uses a power converter interface
- So we will focus mainly on the power electronic interface based RE



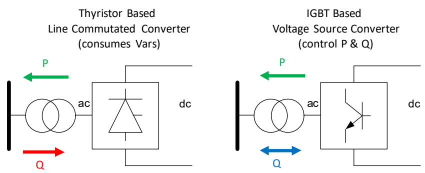
Type 1 – Squirrel-cage induction generator

Type 2 – Wound rotor induction generator with variable rotor resistance

Type 3 – Doubly-fed asynchronous generator

Type 4 – Full converter interface

What is the power electronic interface?



The typical RE grid interface

What is the power electronic interface?

- A full-converter interface means that the grid side converter acts as an inverter, changing dc current to ac current
- The converter being a VSC it is able to independently, and very quickly, control P (MW) and Q (Mvar) to within the converter ratings
- This means great flexibility (voltage control, etc.)
- Type 3 wind turbines are very similar, thought not full-converter interface (more later)

Modeling and Dynamic Performance

- Power electronic interface energy sources are different to synchronous generation
- They can be more flexible and faster to respond
- They can provide voltage support, reactive support, and both fast and temporarily frequency, and sustained primary frequency response
- To provide sustained primary frequency response, some of the incident energy must be curtailed and kept in reserve – this has economic implications

Dynamic Performance of Renewable Energy Systems

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Basic principle of a RES

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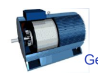
The basic principle is to convert one energy form into another

Kinetic energy → Mechanical energy → Electrical energy

For WTGs:



For PV:

solar irradiation → DC power → Converter to AC power

Variable-Speed Wind Turbine Components

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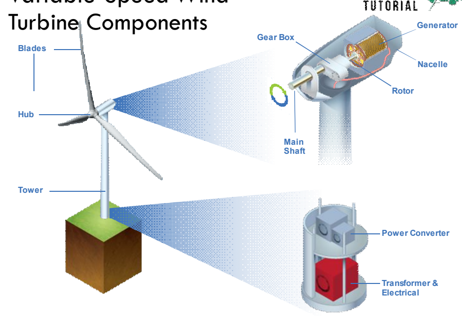

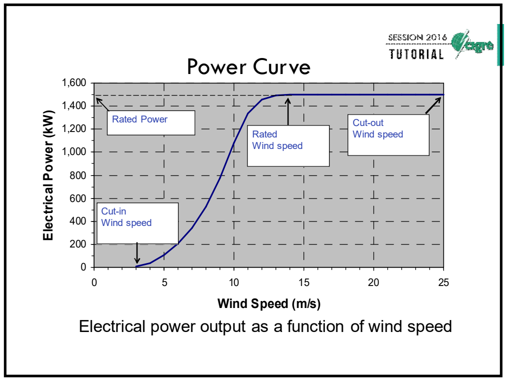
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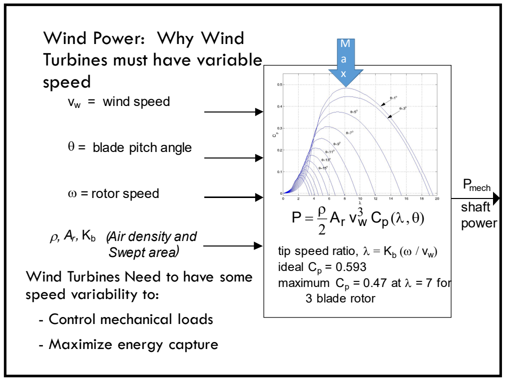
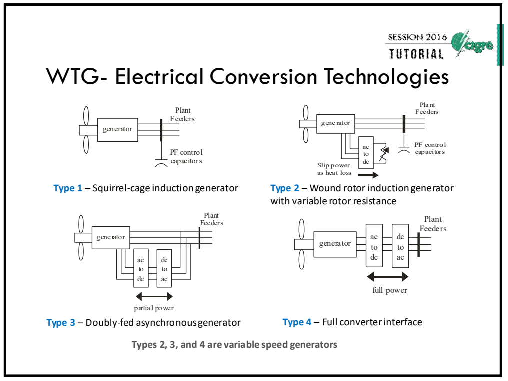
Power Curve
1,600
1,400
1,200
1,000
800
600
400
200
0
Electrical Power (kW)
0
5
10
15
20
25
Wind Speed (m/s)
Rated Power
Rated Wind speed
Cut-out Wind speed
Cut-in Wind speed
Electrical power output as a function of wind speed


Wind Power: Why Wind Turbines must have variable speed
v_w = wind speed
θ = blade pitch angle
ω = rotor speed
ρ, A_r, K_b (Air density and Swept area)
Max
$P = \frac{\rho}{2} A_r v_w^3 C_p(\lambda, \theta)$
tip speed ratio, $\lambda = K_b (\omega / v_w)$
ideal C_p = 0.593
maximum C_p = 0.47 at λ = 7 for 3 blade rotor
P_{mech}
shaft power
Wind Turbines Need to have some speed variability to:
- Control mechanical loads
- Maximize energy capture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WTG- Electrical Conversion Technologies
generator
Plant Feeders
PF control capacitors
Type 1 – Squirrel-cage induction generator
ac to dc
Slip power as heat loss
Type 2 – Wound rotor induction generator with variable rotor resistance
dc to ac
partial power
Type 3 – Doubly-fed asynchronous generator
full power
Type 4 – Full converter interface
Types 2, 3, and 4 are variable speed generators

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What Really is a Doubly-Fed Generator?

- **Physically** – the machine resembles an induction generator
- **Conceptually** – it is like a variable speed, "synchronous" generator with bus-fed excitation
- **Functionally** – it tends to operate more like a current-regulated electronic converter

It is not just a type of "induction generator"; operationally, there is little in common with an induction generator

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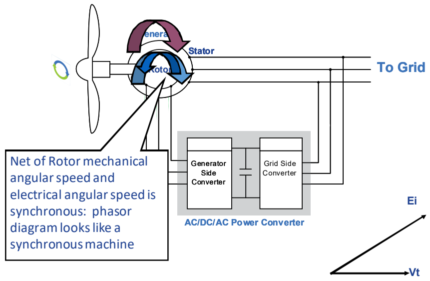
DFG Frequency and Speed (Type 3 WTG)



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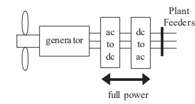
Type 4 and PV



Grid interface controlled completely by grid-side inverter

Voltage Regulation

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Hierarchical Control Philosophy

- **WTG level** – Individual WTGs have fast, autonomous, self-protecting regulation of their terminal voltages - will always respond rapidly and correctly for grid voltage events
- **Wind Plant level** – Plant-level controls meet performance requirements (e.g., voltage regulation) at the point-of-interconnection (POI)
  - Sends supervisory reactive power commands to individual WTGs to 'trim up' initial individual WTG response
  - Coordinates other substation equipment (e.g., switched shunt capacitors)
  - Interfaces with utility SCADA / accepts commands (e.g., voltage reference setpoint) from utility system operator

Reactive Power Capability

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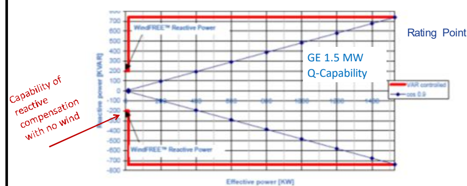

- Steady-state PF range - 0.90 under-excited/0.90 over-excited; Full leading and lagging range over full power range
- Dynamic range meets or exceeds steady-state range
- WTG reactive capability often sufficient to satisfy PF requirements at POI; No need for FACTS devices
- VAR capability reduced at low power due to units cycling off-line
- Faster reactive response than synch. generator

Wind Plant Level Control

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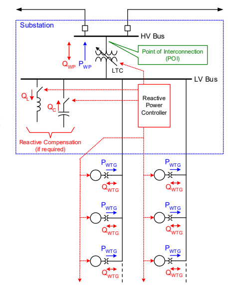
- Coordinated turbine and plant supervisory control structure
- Voltage, VAR, & PF control
- PF requirements primarily met by WTG reactive capability, but augmented by mechanically switched shunt devices if necessary
- Combined plant response eliminates need for SVC, STATCOM, or other expensive equipment
- Integrated with substation SCADA



Actual measurements from 162MW WPP

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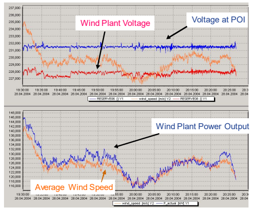

Voltage and Reactive Power Regulation Like a Synchronous Power Plant

Frequency Response

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- Grid must maintain balance between load and generation
- Large disturbances, particularly trips of large generating plants, cause unbalance that must be corrected by "Frequency Response"
- Frequency response covers multiple time frames
  - inertial response (up to a few seconds)
  - governor response ("Primary Response" – 1s to 10s of seconds)
  - AGC response ("Secondary Response" - tens of seconds to tens of minutes)
- ***Committed*** synchronous generation ***naturally*** contributes to system inertia.
  - inertial response for these resources is ***not controllable***, and is not a function of loading level
- ***Some*** synchronous generation provides governor response, ***if***
  - (a) governors are enabled ***and***
  - (b) it has "headroom" to increase output

Wind Plant Frequency Responsive Controls

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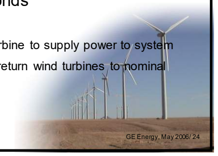
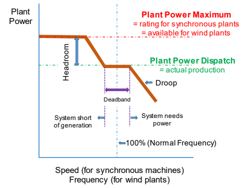
- Governor control responds
  - to both frequency drops and increases
  - in 5-60 second time frame
  - requires curtailment to be able to increase power
  - this is either Fast Frequency Response, or Primary Frequency Response (depending on aggressiveness of the control)
- Inertial control ("synthetic", "virtual") responds
  - Up to 10-second time frame
  - uses inertial energy from rotating wind turbine to supply power to system
  - requires energy recovery from system to return wind turbines to nominal speed
  - more responsive at higher wind speeds
  - this is Fast Frequency Response, NOT System Inertial Response



Primary Response: Wind and Synchronous Gens

- **Over vs. Under-frequency Response**
- Low or zero opportunity cost or variable cost on over-frequency response
- Under-frequency response *can* have high opportunity or variable cost



- **"Droop "**
- Is the change in power output per change in frequency. But be careful: higher (**more**) droop means **less** aggressive response; lower slopes in the curve.
- Can be asymmetric. Wind, and especially PV, can easily have different over- versus under-frequency droop characteristics. Rules should make it possible to take advantage of this.

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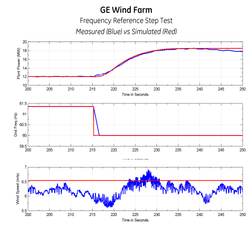
Field Test and Model of Wind Plant Frequency Response



- 83 MW plant
- Test is *release* of high frequency input
- Std GE WTG model (wndtge); parameters tuned for this plant

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Inertia-based Fast Frequency Control

a.k.a. "Synthetic Inertia"

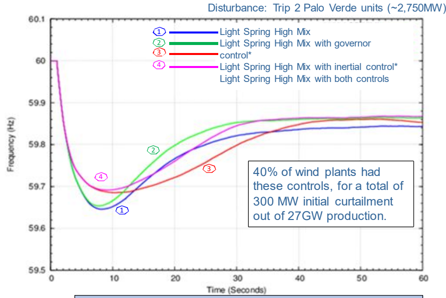
- Use controls to extract stored inertial energy
- Provide incremental energy contribution during the 1st 10 seconds of grid events;
  - Allow time for governors and other controls to act
- Focus on functional behavior and grid response: do not try to exactly replicate synchronous machine behavior

Constraints:

- Not possible to increase wind speed
- Slowing wind turbine reduces aerodynamic lift: Must avoid stall
- Must respect WTG component ratings: loading & electrical ratings
- Must respect other controls:
  - Turbulence management; drive-train and tower loads mgmt

Example: Frequency Control on Wind Plants

Disturbance: Trip 2 Palo Verde units (~2,750MW)



Simulation of Western US in Future High Wind and Solar condition: http://www.nrel.gov/docs/fy15osti/62906.pdf

NREL

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Modeling of Renewable Energy Systems

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Models

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- Model - A set of mathematical equations either algebraic or differential, or both, that constitute a ***mathematical emulation*** of a real physical system.
- So by definition no model is perfect!!
- All models have limitations, and it is important to understand them

Modeling Needs

- Detailed equipment design – vendor specific, internal, highly complex and proprietary models
- Detailed equipment/system interaction studies, e.g. insulation coordination, EMC, torsional-interactions, etc.
  - Vendor specific models are needed
  - EMT modeling
  - Models again are typically proprietary
- Detailed collector system design and grid interface, particularly for very weak systems (low short-circuit ratio) – again vendor specific models are likely needed

Detailed Vendor Specific Model Usage

- Used in EMT type tools for detailed studies
- Hybrid Simulations:
  - EMT models for RE plant an surrounding interfaced with positive sequence large grid model (e.g. PSCAD + Siemens PTI PSS®E)
- Vendor supplied detailed model encapsulated in a DLL that can be interfaced with different simulation tools
- In many cases, such vendor specific models will come with Non-Disclosure Agreements

Concerns with Detailed Vendor Models in Large Scale Positive Sequence Simulations

- Limited documentation – not easy to debug issues
- Non-Disclosure Agreements – cannot share with reliability entities and other TSOs
- Not portable across commercial software platforms – a lot of effort by Vendor and others to keep multiple versions for different tools and different versions of tools
- Models have been found to interact in some commercial tools – hard to debug

Generic (standard) Models

- CIGRE started effort in 2004 [1]
- Western Electricity Coordinating Council (WECC) continued this work [2], [6], [11], [12], [13] and [14]
- IEC TC88 WG27 is also working on standard models for Wind Turbine Generators [3]
- What is presented here pulls from all these public documents, with a particular focus on the CIGRE and WECC efforts
- EPRI has been also instrumental in funding the R&D behind much of this work

WECC Effort

- 1st Generation Wind Turbine Generator (WTG) models

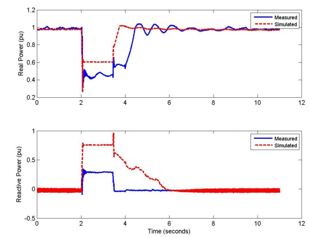
	Model Type	Type 1	Type 2	Type 3	Type 4
PSLF/17	Generator	wt1g	wt2g	wt3g	wt4g
	Excitation / Controller		wt2e	wt3e	wt4e
	Turbine	wt1t	wt2t	wt3t	
	Pitch Controller/Pseudo Gov.	wt1p	wt2p	wt3p	

	Generic model	WT1	WT2	WT3	WT4
PSSE/32	Generator	WT1G	WT2G	WT3G	WT4G
	El. Controller		WT2E	WT3E	WT4E
	Turbine/shaft	WT12T	WT12T	WT3T	
	Pitch control			WT3P	
	Pseudo Gov/: aerodynamics	WT12A	WT12A		

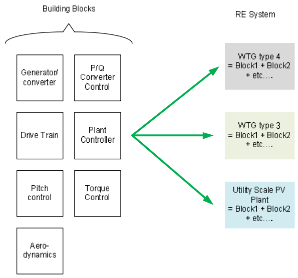
- Were developed ~ 2005 – 2009
- Concerns raised in 2010 with respect to:
  - Type 1 & 2 showing unreasonable frequency response
  - Type 3 & 4 not matching multiple vendors

Response of 1st Generation Generic WTG Models

1st Generation WTG model versus actual WTG response Type 3 WTG (WTG is not GE)

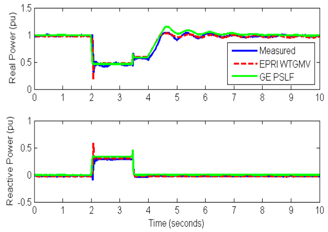


2nd Generation Generic WTG Models

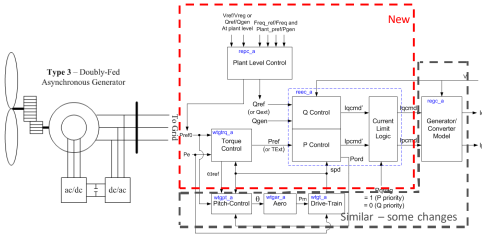


2nd Generation Generic WTG Models

Just one example – ran many tens of cases of comparisons between measurement and simulation for those who provided data



TYPE 3 WTG



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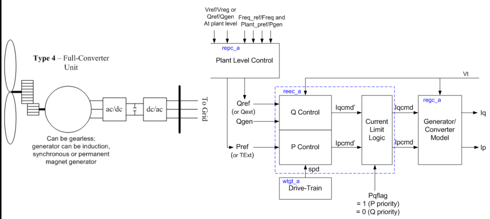
TYPE 4A WTG



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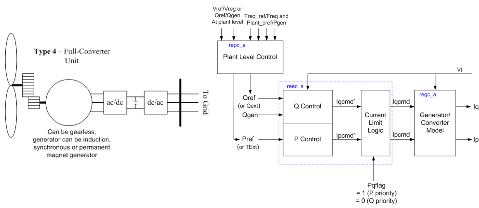
TYPE 4B WTG



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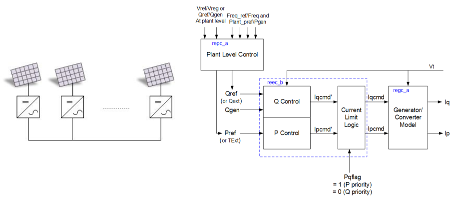
Utility Scale PV



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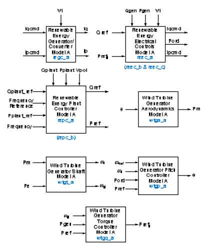
Modeling Various RES

RES	Model Combination
Type 3 WTG	regc_a, reec_a, repc_a, wtgt_a, wtga_a, wtgp_a, wtgq_a
Type 4 WTG	regc_a, reec_a, repc_a (optional: wtgt_a)
PV plant	regc_a, reec_b (or reec_a), repc_a
Battery Energy Storage	regc_a, reec_c (optional: repc_a)



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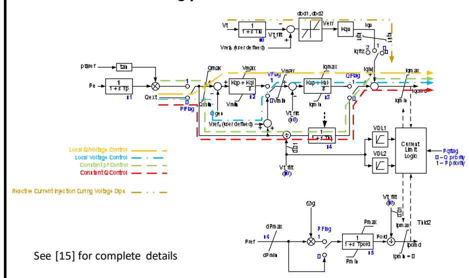
The Core Module: Renewable Energy Electrical Controls



See [15] for complete details

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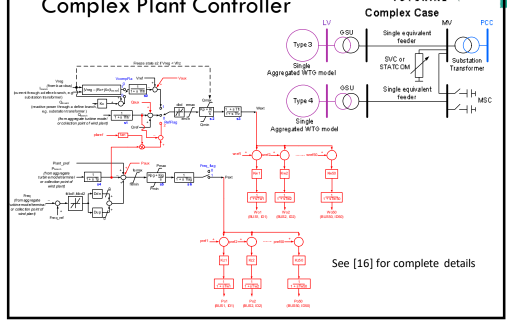
New Feature: Complex Plant Controller



See [16] for complete details

VALIDATION SINGEL WTG Type 3 [16]

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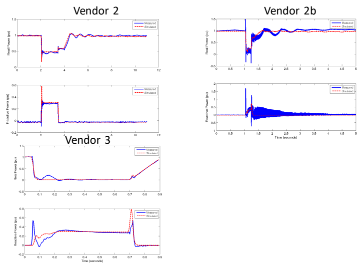

VALIDATION SINGEL WTG Type 4 [16]

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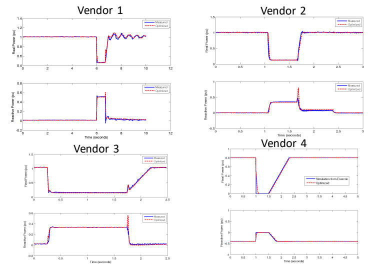

VALIDATION

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- Validation cases have been done with wind power plants using PMU disturbance data [16]
- Validation cases have been done with PV and Energy storage systems as well [16].
- Certainly more work can be done and certainly there are improvements that can be made to the models as learning increases with their application

Present Status

- WECC Models have been implemented and tested/compared across several commercial tool platforms (Siemens PTI PSS®E, GE PSLF™, PowerWorld Simulator, PowerTech Labs TSAT)
- Have been also adopted by some European tools and tested to some extent (DigSilent PowerFactory)
- There are known difference between WECC and IEC generic models:
  - Active drive-train damping emulation
  - Simple emulation of active crow-bar
  - Integrator state reset on torque controller

Value of Generic Models

- Portability – standard and portable across several commercial platforms
- Public – documented and open, so they can be debugged
- Validation – as shown they have been validated against several vendor equipment to show reasonable performance
- Modeling future systems – useful for modeling futuristic studies where looking at different potential penetration levels of RES

Limitations of Generic Models

- Not good for looking at details of unbalance faults/conditions – these are positive sequence models
- Limited bandwidth of validity – true of majority of models in large scale simulations
- Not good for studying very weak systems
- Assume constant wind speed (solar irradiation)
- Presently do not offer modeling of "synthetic inertia"; however, they can model and have been validated for modeling primary frequency response

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Further Reading:

[1] CIGRE Technical Brochure 328, Modeling and Dynamic Behavior of Wind Generation as it Relates to Power System Control and Dynamic Performance, Prepared by CIGRE WG C4.601, August 2007. (www.e-cigre.org)

[2] A. Ellis, P. Pourbeik, J. J. Sanchez-Gasca, J, Senthil and J. Weber, "Generic Wind Turbine Generator Models for WECC – A Second Status Report", Proceedings of the IEEE PES GM 2015, Denver, CO, July 2015.

[3] J. Fortmann, P. Pourbeik, N. Miller, Y. Kazachkov, J. Bech, B. Andresen and P. E. Sørensen, "Wind Plant Models in IEC 61400-27-2 and WECC - latest developments in international standards on wind turbine and wind plant modeling", Conference: 14th International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Power Plants, October 2015.

[4] G. Lammert, L. D. P. Ospina, P. Pourbeik, D. Fetzer, M. Braun, "Implementation and Validation of WECC Generic

Photovoltaic System Models in DIgSILENT PowerFactory", to be published in the Proceedings of the IEEE PES GM, July 2016.

[5] EPRI Report, Generic Models and Model Validation for Wind and Solar PV Generation: Technical Update, Product ID 1021763, December 2011 http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000000001021763

[6] WECC Solar Plant Dynamic Modeling Guidelines, April 2014 https://www.wecc.biz/Reliability/WECC%20Solar%20Plant%20Dynamic%20Modeling%20Guidelines.pdf

[7] Western Wind and Solar Integration Study (NREL) http://www.nrel.gov/docs/fy10osti/47434.pdf

[8] Western Wind and Solar Integration Study – Phase 3 (NREL) http://www.nrel.gov/docs/fy15osti/62906.pdf

[9] EPRI/NREL Report on Active Power Control for Wind http://www.nrel.gov/docs/fy14osti/60574.pdf

[10] Eastern Frequency Response Study by GE http://www.nrel.gov/docs/fy13osti/58077.pdf

Further Reading:

[11] WECC 2nd Generation WTG Model Specifications: https://www.wecc.biz/Reliability/WECC-Second-Generation-Wind-Turbine-Models-012314.pdf

[12] WECC PV Model Specifications: https://www.wecc.biz/Reliability/WECC-Solar-PV-Dynamic-Model-Specification-September-2012.pdf

[13] WECC PV Modeling Guide:
https://www.wecc.biz/Reliability/WECC%20Solar%20Plant%20Dynamic%20Modeling%20Guidelines.pdf

[14] WECC WTG Modeling Guide:
https://www.wecc.biz/Reliability/WECC%20Wind%20Plant%20Dynamic%20Modeling%20Guidelines.pdf

[15] EPRI Report, Model User Guide for Generic Renewable Energy System Models, 2015
http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000003002006525

[16] WECC REMTF Workshop
https://www.wecc.biz/Reliability/Wkshp_WECC_REMTF_Workshop_2016.pdf

[17] WECC White Paper, Value and Limitations of the Positive Sequence Generic Models for Renewable energy Systems, December 2015.
https://www.wecc.biz/_layouts/15/WopiFrame.aspx?sourcedoc=/Administrative/White%20Paper%20Generic%20Model%20Limitations%20December%202015.docx&action=default&DefaultItemOpen=1

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